Fermilab FERMILAB-Conf-04/074-E June 2004

BOTTOM AND CHARM MASSES AND LIFETIMES AT THE TEVATRON; AND A PENTAQUARK SEARCH

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Abstract

The Fermilab Tevatron, operating at $\sqrt{s} = 1.96$ TeV, provides a rich environment for the study of the bottom and charmed hadrons and for searches of other bound states. Presented here are recent measurements of the masses of the following states using fully reconstructed events: B^+, B^0, B_s, Λ_b, and the neutral B^{**}. Lifetimes from both CDF and D0 in exclusive decays for all of these modes are also presented (sans the B^{**}). A search was conducted at CDF for the Ξ^{--} and Ξ^0 pentaquark states in the decay $\Xi(1860) \rightarrow \Xi^- \pi^\pm$ setting a limit on their production in $p - \overline{p}$ collisions relative to the number of $\Xi(1530)$ baryons seen.

1 Introduction

This article presents recent results from the Fermilab Tevatron on the masses and lifetimes of the hadrons containing a bottom quark. In addition a recent search for two pentaquark states has been completed.

The study of masses and lifetimes of the heavy quark states is motivated by the theoretical framework of Quantum Chromodynamics (QCD). QCD provides the binding force for hadrons and therefore is a large factor in contributing to the mass of a quark bound state. In the case of a hadron's lifetime, even though it is primarily governed by a short distance weak decay, QCD can suppress decays which require specific colour charge configurations and also governs the likelihood that specific types of hadrons will appear in the final state.

Since QCD is a non-perturbative force, it can be difficult to predict even the simplest properties of basic mesons. The heavy quark sector provides us with a window into this world because the presence of the heavy quark brings with it a new energy scale the size of the heavy quark mass (~ 4.5 GeV/c^2 in the case of the b quark) which is substantially higher than the characteristic scale of colour confinement (~ 0.2 GeV). Consequently it is possible to construct a theoretical approximation called the Heavy Quark Expansion (HQE) which is a recasting of QCD to a realm where the heavy quark is given an infinite mass relative to the light quarks. [1] A double expansion in the colour coupling constant and the mass of the heavy quark then provides a perturbative set of predictions for hadronic masses and lifetimes which can be checked by experiments.

The results presented in these proceedings are from recent measurements taken at the Fermilab, Tevatron with the D0 and CDF detectors. [2, 3] First this report will present the mass measurements. Next are explained recent results on the B meson and baryon lifetimes. And finally results of a search for the Ξ^{--} and Ξ^0 pentaquark states will be shown. These results were all taken at the Fermilab Tevatron with a center of mass energy of $\sqrt{s} = 1.96$ TeV and represent results from either the Collider Detector (CDF) or the D0 experiments.

2 Bottom Hadron Masses

The masses of several B hadrons have been measured at the Tevatron. Presented here are the masses of the $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, $B_S^0 \to J/\psi \phi$, $\Lambda_b \to J/\psi \Lambda$, and the $B_d^{**} \to B^+ \pi^-$.

2.1 Experimental procedure and Results

The CDF and D0 detectors have magnetic fields throughout their tracking volume and can therefore reconstruct masses of particles decaying into charged final states to the level of ~ 1.0 MeV/c^2. The CDF experiment has preliminary results on most of the mass measurements, so their procedure will be described. The $J/\psi \rightarrow \mu^+\mu^-$ provides an easily recognizable signature with which to fix the energy scale and correct for energy losses in the detector. Though not an actual mass measurement, the $\psi(2s) \rightarrow J/\psi\ \pi^+\pi^-$ is also used to monitor the effects of the mass measurement for different cuts and tests of the systematic uncertainties. Corrections were made for the energy loss in the detector by plotting the J/ψ mass as a function of transverse momentum (p_T) which revealed a linear dependence of the dimuon mass on the p_T of the J/ψ prior to corrections.

After all other corrections have been applied, there was also an offset to the world average mass amounting to ~ 5 MeV/c^2 that is interpreted as a shift in the absolute scale of the magnetic field. Variations in the mass as functions of the direction of the J/ψ in the $x-y$ plane, the difference in curvature between the two muons, and the difference in dip angle between the two muons have been observed. These variations can be attributed to the need for alignment improvements between the silicon and central tracking detectors but still amount to a mass variation less than ± 1.0 MeV/c^2. A study of the time dependence of the magnetic field was conducted showing less than ± 0.5 MeV/c^2 variation with time (after previous corrections have been applied). When all corrections have been applied the mass of the $\Upsilon \rightarrow \mu^+\mu^-$ obtained is 9461 ± 1.5 compared to the world average value of 9460.30 ± 0.26 MeV/c^2 from the Particle Data Group (PDG). [4]

For the B hadron search, the analysis cuts are optimized for the significance of each meson by selecting cuts which maximize either $S^2/(S+Bkg)$ or S^2/Bkg. The final fit of the tracks constrains all the tracks to come from a single vertex and further constrains the mass of the two muon tracks to the world average J/ψ mass.

The largest systematic uncertainty in these measurements comes from the the function used to fit the mass peak. A shift in the mass is observed when the mass constraint on the J/ψ is removed. This is the single largest effect on the mass fit and contributes ± 0.8 MeV/c^2 to the systematic uncertainty.

Table 1 shows the all of the recent results on the masses obtained by the CDF experiment. In addition there is evidence for the $B_d^{**} \rightarrow B^{\pm}\ \pi^{\mp}$ reported by the D0 experiment at a mass of 5710.0 ± 1.6 MeV/c^2 The B^{**} refers collectively to a group of four excited mesons with $l = 1$ and which decay through pion channels to both the ground state B meson and the $s = 1$ B^* meson states. [5] Further measurements of hadronic bound states can be expected in the future from both CDF and D0.

Table 1: *Tabulated are measurements of B hadron masses measured by the CDF experiment. D0 has seen evidence for one of the decays of the B_d^{**} meson. This is reported in the text. The first uncertainty is statistical and the second is systematic.*

Hadron	Mass (MeV/c^2)
B^0	$5280.30 \pm 0.92 \pm 0.96$
B^+	$5279.32 \pm 0.68 \pm 0.94$
B_s	$5365.50 \pm 1.29 \pm 0.94$
Λ_b	$5620.4 \pm 1.6 \pm 1.2$

3 Lifetimes and Lifetime Ratios

3.1 Predictions from the HQE

Below are listed the current predictions from the Heavy Quark Expansion for the ratios of lifetimes for several of the more common B hadrons. [6, 7] These predictions are Next-to-Leading-Order (NLO) calculations.

$$\frac{\tau(B^+)}{\tau(B^0)} = 1.06 \pm 0.02 \tag{1}$$

$$\frac{\tau(B_S)}{\tau(B^0)} = 1.00 \pm 0.01 \tag{2}$$

$$\frac{\tau(\Lambda_b)}{\tau(B^0)} = 0.88 \pm 0.05 \tag{3}$$

3.2 Experimental Methods and Results

All of these analyses use the $J/\psi \to \mu^+\mu^-$ trigger as the data source. For both CDF and D0 this trigger requires two muons with enough momentum to pass through the material in the detectors' calorimeters (between 1.5 and 3.0 GeV/c depending on experiment and the exact direction of the muon). The D0 experiment has muon coverage out to pseudorapidity ($|\eta|$) less than 3.0 while CDF is limited to $|\eta| < 1.1$.[1] The exact luminosity collected varies between the different channels as shown in Table 2.

In both experiments muons must make a good match with tracks in the central tracker and must also contain hits in the silicon chambers. Once good muons forming J/ψ candidates are selected they are combined with other good tracks, also with silicon hits to form exclusive B hadron final states.

[1] $\eta = -\ln(\tan\theta/2)$ where θ is the angle with respect to the proton beam.

Table 2: *Shown are measurements of B hadron lifetimes obtained by the CDF and D0 experiments. Also presented separately is the ratio of the charged to neutral B meson lifetime. The first uncertainty is statistical and the second is systematic.*

Measurement	Lifetime (ps) or ratio	Expt.	$\int L\,dt$
$\tau(B^+)/\tau(B^0)$	$1.080 \pm 0.042(tot.)$	CDF	240 pb^{-1}
$\tau(B_s)/\tau(B^0)$	$0.890 \pm 0.072(tot.)$	CDF	240 pb^{-1}
$\tau(B^0)$	$1.539 \pm 0.051 \pm 0.008$	CDF	240 pb^{-1}
	$1.51^{+0.19}_{-0.17} \pm 0.20$	D0	115 pb^{-1}
$\tau(B^+)$	$1.662 \pm 0.033 \pm 0.008$	CDF	240 pb^{-1}
	$1.630 \pm 0.083 \pm 0.096$	D0	115 pb^{-1}
$\tau(B_s)$	$1.33 \pm 0.10^{+0.008}_{-0.010}$	CDF	240 pb^{-1}
	$1.19^{+0.19}_{-0.16} \pm 0.14$	D0	115 pb^{-1}
$\tau(\Lambda_b)$	$1.25 \pm 0.26 \pm 0.10$	CDF	65 pb^{-1}
$\tau(Inclusive\ B)$	$1.561 \pm 0.013 \pm 0.047$	D0	115 pb^{-1}

There are two main methods currently employed in lifetime measurements. The first uses the sidebands both above and below the invariant mass of the B hadron where there is essentially no signal to determine the background distribution in proper decay length ($c\tau$). A fit to the background is performed using a central Gaussian peak, for the prompt background, and one or two exponential distributions to account for partially reconstructed and misreconstructed B hadron backgrounds. Once the background distribution in $c\tau$ is known, these parameters are fixed while the fit is performed under the signal peak. Only an additional 'signal' exponential (usually convoluted with a resolution function) is added to the fit so there are only one or two free parameters. This method was used to fit the Λ_b lifetime.

The second fit method is more complicated but more completely utilizes the discriminating power of the decay mode's mass distribution. For nearly all of the lifetime measurements presented here a multivariate likelihood fit to both the lifetime and mass is performed simultaneously. The fitting function is invariably more complicated because fits to signal and sideband parameters, weighted by the event's proximity in mass to the mean particle mass, are essentially performed at the same time. The likelihood functions typically contain a central Gaussian and up to 4 different exponential tails, one of which is the signal distribution. These distributions are multiplied by the Gaussian and background models for the mass and fit all at once. Figure 1 shows the results of this kind of procedure from the D0 experiment. Table 2 shows all of the most recent lifetime measurements obtained from the two experiments.

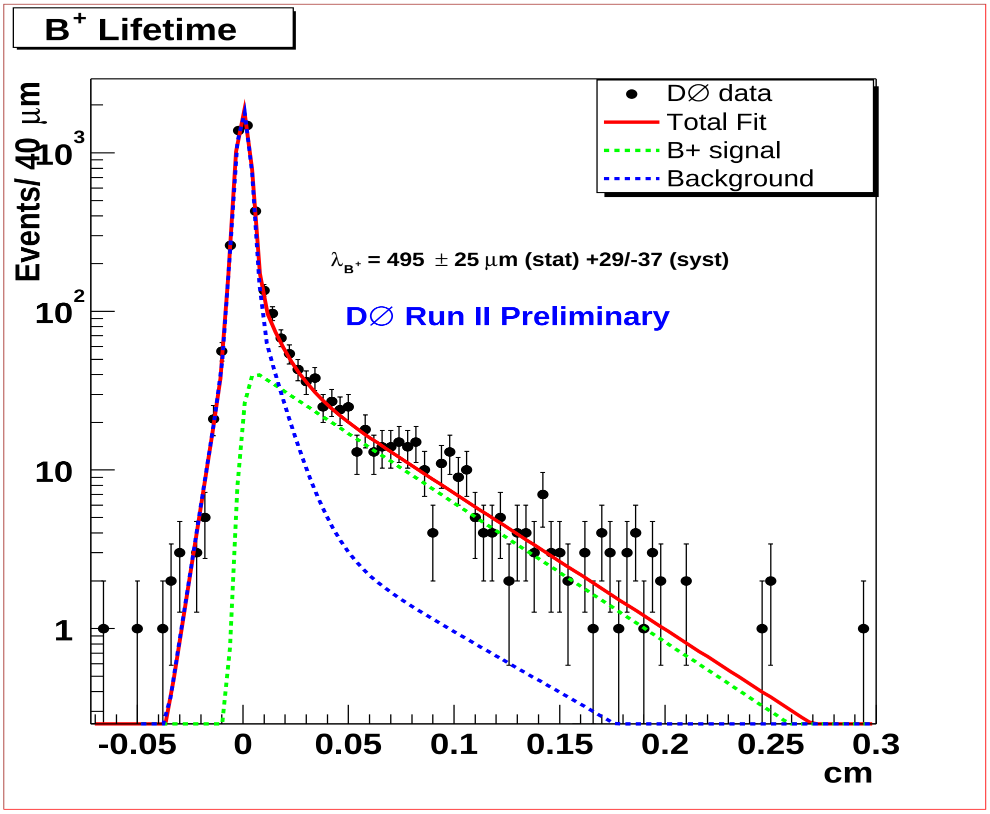

Figure 1: *Shown are the data and fit results for the decay $B^+ \to J/\psi K^+$ from the D0 experiment. The long-lived tail due to the signal is clear as well as the background contributions.*

Figure 2 shows the results of Table 2 against measurements from the BaBar [8] and BELLE [9] experiments. As well as competing with these experiments, the Tevatron experiments hold out the possibility of measuring a series of B meson and baryon lifetime ratios within a given experiment.

4 Pentaquark Search

The properties of colour confinement allow only states neutral in the colour charge because of the relative strength of the strong nuclear force. Since each quark can only carry one type of colour charge, and since there are three colour charges, it then follows fairly intuitively that quark bound states will come in groups of three forming all known and predicted baryon bound states. Throw in the anti-quarks with their corresponding anticolours and the meson bound states then follow.

Within QCD though, more exotic combinations can be constructed while

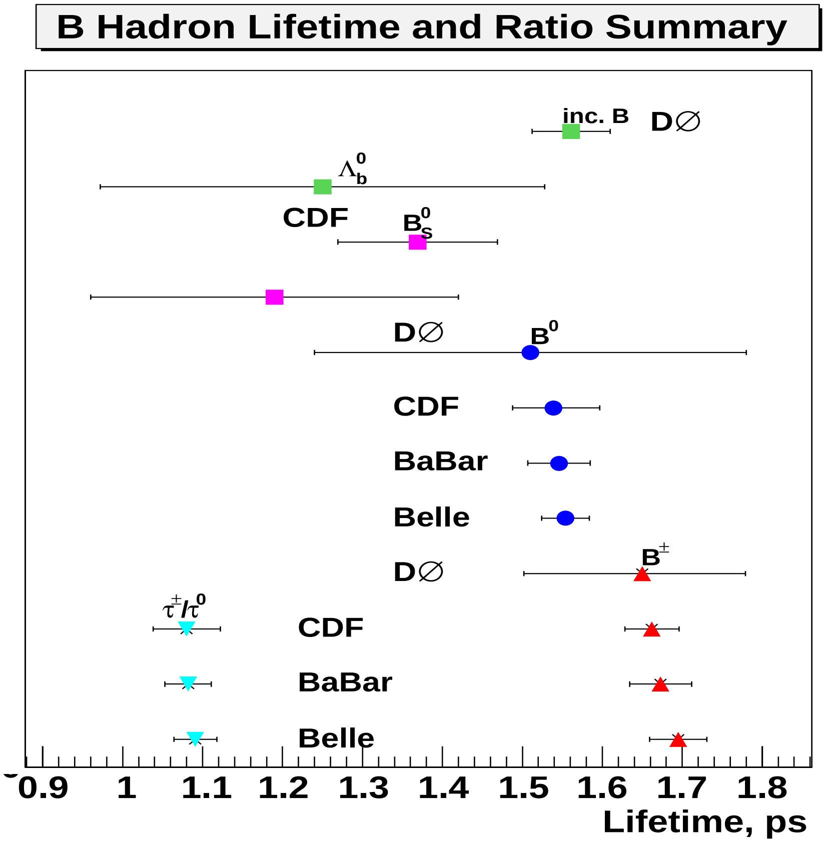

Figure 2: *The hadronic lifetimes from Table 2 are plotted together along with measurements of the charged and neutral B mesons from the BABAR* [8] *and BELLE* [9] *experiments. The systematic and statistical uncertainties have been combined in quadrature.*

still maintaining the constraint of colour neutrality, the most familiar example being the nuclei of the elements. The pentaquark is another such extension; a narrow, bound state consisting of 4 quarks plus one anti-quark. Conceptually, and also in the formalism of group theory, this can be thought of as one three quark multiplet and one quark-antiquark multiplet combined.

Using the framework of group theory within the context of flavor SU(3) it is possible to construct multiplets of pentaquark states which are the 5-quark analogues of baryon three quark multiplets. The combination is performed by using the SU(3) multiplet from the quark triplet part of the pentaquark with the quark-antiquark part. This is mathematically the same as combining two higher order SU(3) multiplets within the same SU(3) group formalism. When this is done for a 5-quark configuration the result yields a symmetric anti-decuplet and an octet of mixed symmetry.

The newly combined multiplets form structures in the Isospin–Weak Hy-

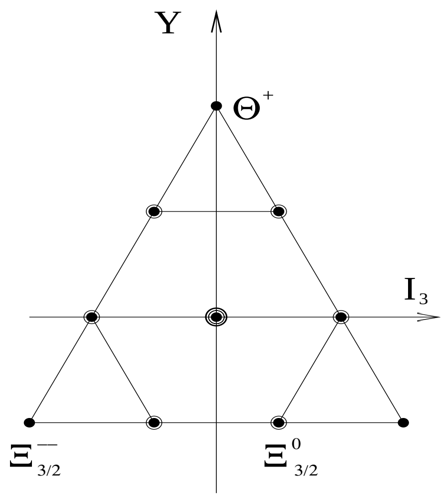

Figure 3: *Combinations of quarks, assuming SU(3) flavour symmetry, produce groups of fixed symmetry in the Isospin–Hypercharge ($I_3 - Y$) plane. Shown here is the diagram produced that results when combining four quarks and one antiquark using SU(3). A symmetric anti-decuplet and an octet of mixed symmetry are obtained. The CDF analysis focuses on the two Ξ states labeled in this diagram.*

percharge ($I_3 - Y$) plane shown in Figure 3. Therefore, somewhat confusingly, the same symbolic convention for the proposed pentaquark states as the standard baryons is used. So the particles forming the bottom row of the symmetric pentaquark decuplet are the Ξ mesons. The apex of this decuplet is designated the Θ. Though these mathematical associations from the properties of group theory can be reproduced by anyone who has studied that formalism at even a relatively elementary level, that such multiplets would appear in nature as tightly bound states is less clear.

4.1 Experimental search

Several experiments have reported the observation of the Θ^+ pentaquark. [10)] At least one experiment has reported seeing a signal of the Ξ pentaquark state when the Ξ^{--} and Ξ^0 (and antiparticle states) are all combined. [11)] Being a hadron collider, the Tevatron should produce these amazing states if they exist and therefore a search has started.

Reported on here is the search of the CDF experiment for the Ξ^{--} and the Ξ^0 pentaquark states. The Ξ^{--} would have valence quarks $dssd\overline{u}$ while the Ξ^0 would contain $dssu\overline{d}$. The following decay chain is used to search for the Ξ states (which matches the search performed by NA49 [11]).[2]

$$\Xi_p^{--} \rightarrow \Xi^- \, \pi^- \quad \text{and} \tag{4}$$

$$\Xi_p^{0} \rightarrow \Xi^- \, \pi^+ \tag{5}$$

In both searches the decay $\Xi^- \rightarrow \Lambda \, \pi^-$ with $\Lambda \rightarrow p \, \pi^-$ allows for complete reconstruction in CDF's tracking volume.

Two independent trigger samples are used in the search. The first, which contains more data, is the Two Track Trigger (TTT) which requires that each event have two tracks of opposite charge with $p_T > 2.0$ GeV/c, both with an impact parameter greater than 100 μm in the silicon trigger. When this cut is applied at the trigger level, very few of the events chosen as pentaquark candidates will have any tracks that were actually involved in this trigger. Consequently, these samples will contain high levels of bottom and charm hadrons in addition to any potential pentaquarks. The worry was that this might produce a physics bias against pentaquark formation so the experimental technique was also performed on a trigger sample of 20 GeV jets (Jet20 sample) which only require that an energy greater than 20 GeV be deposited in a contingent cluster of calorimeter towers. Tracking is not required in the Jet20 trigger, however its high rate means that this trigger is prescaled. Therefore it has less integrated luminosity over the same running period.

The search is performed in the following manner. First oppositely charged tracks are combined to form candidates for the Λ baryon. The vertex location of the Λ candidate must be more than 1 cm from the primary vertex and the momentum vector is then combined with another charged track to form the Ξ^- candidate. Ξ^-'s are relatively long lived and therefore can leave hits in the silicon detector before they decay. Consequently, in order to reduce the combinatoric background, the Ξ^- candidate momentum vector and vertex position is used as a seed to search for hits in the silicon detector. Events which do not have sufficient numbers of hits in the silicon within that seed are removed as possible candidate events. The good Ξ candidates are then combined with the appropriately signed pions to search for the Ξ_p pentaquarks and their antiparticle equivalents.

Figure 4 shows the final search in the TTT data for the doubly charged and neutral particle cases (the charge conjugate states are also included in this plot). One encouraging feature of this plot is the prominent appearance of the neutral $\Xi(1530)$ baryon excited state with the same decay chain. This

[2]Henceforth I have added the subscript 'p' to denote the pentaquark state in order to distinguish it from the more conventional Ξ baryons.

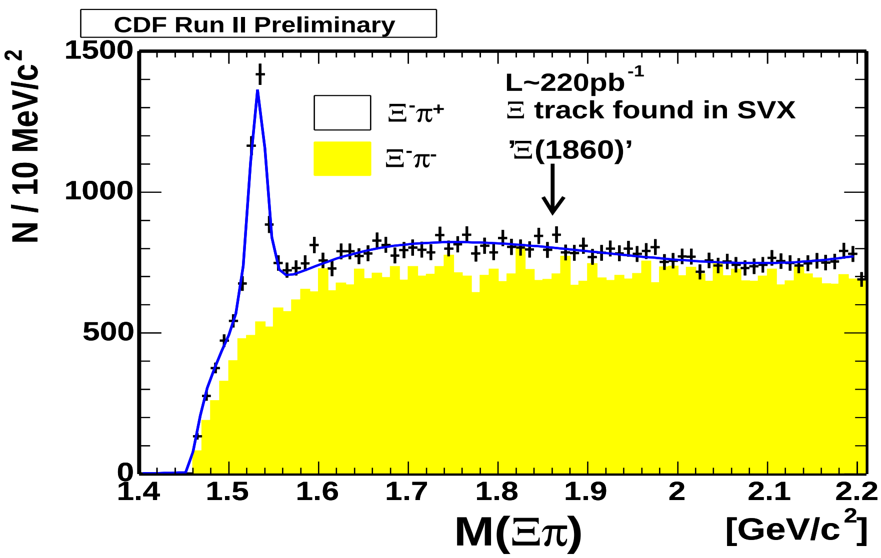

Figure 4: *Shown are the invariant mass plots for* $\Xi^-\pi^+$ *(open) and* $\Xi^-\pi^-$ *(yellow or shaded) from the TTT data sample. There is no evidence for a narrow resonance in these plots apart from the well-known* $\Xi(1530)$ *and in particular no evidence near 1860 MeV/*c^2.

provides CDF with a convenient known resonance against which to gauge the acceptance of the pentaquark search against other experiments and to fix a relative production rate. There is no evidence of the Ξ_p in the expected mass range so Table 3 displays the limits that the CDF experiment can set in the TTT data.

The CDF group has formed a further subgroup to perform a more systematic and thorough search for long-lived pentaquark bound states. This group will use several different decay modes and trigger samples in an attempt to confirm the existence of these particles during the summer of 2004.

5 Conclusions

The presence of highly accurate tracking detectors in the solenoidal magnetic fields of the CDF and D0 permit measurements of the highest accuracy in

Table 3: *Shown are the limits on the production of* Ξ_p *pentaquark states relative to the production of the* $\Xi(1530)$ *for the Two-Track Trigger (TTT) data sample with* $\int L\,dt = 220\ pb^{-1}$ *for both 90% and 95% confidence levels.*

Channel	90% CL	95% CL
$\Xi^-\pi^+/\Xi(1530)$	0.06	0.07
$\Xi^-\pi^-/\Xi(1530)$	0.03	0.04

the world for those meson and baryon b quark states that cannot be directly produced as a resonance in an electron-positron machine.

There seem to be no surprises in store thus far in the measurements of the lifetimes of the B hadrons for τ^+/τ^0 as given in Equation (1). Experimental measurements are already approaching the accuracy of the ratios given in Equations (2) and (3). τ_S/τ^0 is still coming out quite low. This may be reflecting the CP-even content of the decay mode studied, since we expect lifetime discrepancies bewteen the two CP eigenstates of the B_s meson. Whether or not we uncover discrepancies between our predictions and reality, our understanding of hadronic bound states will advance as the Tevatron continues to run.

CDF has conducted a search sensitive to the proposed Ξ_p^0 and Ξ_p^{--} bound 5-quark (or pentaquark) state. The search as reported here was unable to see either of these states even though the excited baryon state $\Xi(1530)$ was clearly visible. There is a more extensive on-going effort at the Tevatron to search for other types of pentaquark states. One does wonder though why such states have remained unseen despite several hadron fixed target experiments running through the early 1980's. [12]

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